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Data-driven reliability analysis of Boeing 787 Dreamliner

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Abstract The Boeing 787 Dreamliner, launched in 2011, was presented as a game changer in air travel. With the aim of producing an efficient, mid-size, wide-body plane, Boeing initiated innovations in product and process design, supply chain operation, and risk management. Nevertheless, there were reliability issues from the start, and the plane was grounded by the U.S. Federal Aviation Administration (FAA) in 2013, due to safety problems associated with Li-ion battery fires. This paper chronicles events associated with the aircraft's initial reliability challenges. The manufacturing, supply chain, and organizational factors that contributed to these problems are assessed based on FAA data. Recommendations and lessons learned are provided for the benefit of engineers and managers who will be engaged in future complex systems development.

1. Introduction

Boeing, one of the world's largest aerospace companies, manufactures products that include commercial aircraft and defense, space, and security systems. Boeing's commercial aircraft business has been in service for nearly 100 years, and its current fleet includes the 737, 747, 767, 777, and 787 families.[1] The Boeing 787 Dreamliner was introduced to the market in 2011 as a mid-size, dual-aisle, wide-body aircraft. Boeing marketed the 787 as a revolutionary aircraft, with an array of new features that would increase fuel efficiency by 20% and improve passenger comfort.[2]

Some of the key design innovations in the 787 included the use of composite materials in the wings and fuselage[3]; Li-ion batteries to power up aircraft systems even before the engine has started, to provide backup to critical loads and support of battery-only braking; and a no-bleed electrical system architecture.[4] It was also the first time that Boeing replaced the traditional pneumatic system with an electrical power-generating system for starting the engine, anti-icing the wings, and maintaining cabin pressure.[5] Boeing incorporated the ability to use two types of engines (General Electric's GEnx and Rolls Royce's Trent 1000).[6] Collectively, these and other design changes were introduced to lower operating costs, improve fuel efficiency and cruising speeds, and reduce maintenance costs.[7]

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The path to profitability and realization of these aims was tortuous for Boeing.[8] The grounding of the 787 in 2013 focused the spotlight not just on the Li-ion batteries, but also on other issues that came to light with the Critical Systems Review Team (CSRT) report.[9] Furthermore, the recent fatal incidents involving the 737 MAX have refocused the attention on the reliability of Boeing's aircraft. In particular, the *New York Times* reported that Boeing has been fostering a culture of pushing products in the market faster rather than ensuring product quality, especially in the South Carolina factory where the 787 s are manufactured.[10] A study and interviews conducted with current and former employees of Boeing, ranging from floor technicians to quality managers, suggest that the quality of Boeing aircraft has become compromised[10] and quality issues have spread to defense aircraft as well. According to CNN, the U.S. Air Force has been returning some of the delivered aircraft and has even halted deliveries of aircraft due to the ongoing quality problems.[10]

This paper focuses on failure data released in the CSRT report,[9] NTSB reports,[11–13] and the journals referenced in this paper. Using these reports and the incident reports from the aviation community portals, we have collected data to support a reliability growth analysis. This is a first-of-a-kind study of the reliability of the 787 aircraft and provides technical insights into potential contributing factors.

The paper is organized as follows. Section 2 is a chronology of events before and after the order given by the FAA to ground the 787 fleet and includes a discussion of the review conducted by the FAA and Boeing. The development of the data set to support the reliability growth analysis is described in Section 3. In Section 4, the potential contributors to the reliability issues experienced by Boeing are identified. Section 5 presents the lessons learned.

2. Chronology of events

The first 787 was shipped in the first quarter of 2011, with two to follow in the second quarter. By the end of 2012, 49 aircraft had been delivered, primarily to Japanese Airlines.[14] Table 1 shows the number of 787 aircraft sold in each quarter until 2016.

In July 2012, the Japanese airline ANA grounded five of its 787 s due to potential corrosion risk in some of the engine parts.[15] This was followed by even bigger problems revealing themselves in the form of fires in 787 aircraft. Two airplane fires associated with the Li-ion batteries of the plane forced the grounding of the worldwide fleet on January 16, 2013. The specifics of the battery failure are described in.[16] In congressional hearings, Boeing and its suppliers admitted that despite a significant engineering effort of 200,000 hours, they could not identify the root cause of the problem. Nevertheless, Boeing made changes, including a revision of the internal battery components to minimize the chances of initiating a short circuit, as well as better insulation of the cells and the addition of a new containment and venting system.[15] On March 12, after less than one month of testing, the FAA accepted Boeing's redesign.

Table A1 in the Appendix presents a list of the 787's technical issues reported to the authorities and/or in the press, prior to the 2013 grounding of the plane due to the Li-ion battery problem. For each event, the authors have attempted to identify the system and component failure modes. This information suggests there was a range of different component failure modes responsible for the failure events.

Table 1 Boeing 787 deliveries in quarters.

Fiscal year quarter No.	Quarter period	Deliveries
3	Jul-Sept 2011	1
4	Oct-Dec 2011	2
1	Jan-Mar 2012	5
2	Apr-Jun 2012	6
3	Jul-Sept 2012	12
4	Oct-Dec 2012	23
1	Jan-Mar 2013	1
2	Apr-Jun 2013	16
3	Jul-Sept 2013	23
4	Oct-Dec 2013	25
1	Jan-Mar 2014	18
2	Apr-Jun 2014	30
3	Jul-Sept 2014	31
4	Oct-Dec 2014	35
1	Jan-Mar 2015	30
2	Apr-Jun 2015	34
3	Jul-Sept 2015	37
4	Oct-Dec 2015	34
1	Jan-Mar 2016	30
2	Apr-Jun 2016	38
3	Jul-Sept 2016	36

Furthermore, the 787's problems persisted even after its "relaunch". Operational problems between September 2013 and January 2016 are shown in Table A2 in the Appendix.

In July 2014, after three months of redesign and requalification of batteries, Boeing conceded in a press release that the reliability of the 787 was below their initial expectations and below that of their earlier 777 model.[17] At the same time, they once again attempted to reassure stakeholders that they and their suppliers had already identified suitable corrective actions and initiated or fully implemented them.

3. Reliability growth analysis

Reliability Growth Analysis (RGA) is used in modeling, designing, and improving repairable systems. It is intended to prove the reliability performance of a new or existing product, component, or system over time. To assess this growth, we examined failure events reported in commercial aircraft journals and the NTSB database (listed in Table A1 and A2). As the data on the life (time in service) of the components responsible for the events of Tables A1 and A2 are not available, we use the count of events per month (based on reports in [18,19] and make the assumption that all defective components are replaced. Based on this, a dataset of the number of events per month has been created and is shown in Table A3 in the Appendix. To determine the total time on test for the aircraft fleet, the following additional assumptions were made:

(1) Aircraft hours is based on number of deliveries by Boeing, as reported in their official orders and deliveries information page. For aircraft delivered in one quarter, it is assumed that they do not go into service until the following quarter.

(2) For failure events, it is assumed that a failure in the quarter occurs at the end of that quarter.
(3) The operational period of the aircraft is assumed to be 50% (half of the number of hours in 90 calendar days), based on the report in Refs. [20,21].

Fig. 1 is a time-cumulative event plot of event data from Table A1 and A2 and other databases mentioned above. We note that the slope of the plot decreases with increasing time. This is indicative of increasing reliability. The Duane plot in Fig. 2 shows the trend of cumulative Mean Time Between Failures (MTBF) over the flight hours. It can be seen that there is a sharp inflection point at around 115000–160000 hours, which corresponds to the period in the first quarter of 2013. The approximately straight line after the inflection point suggests that the data are consistent with an NHPP (Non-Homogeneous Poisson Process) power law model, which allows us to model the reliability growth using the Crow-AMSAA model.[22]

The Crow-AMSAA model is generally used to assess reliability growth during development testing. One of the assumptions of the Crow-AMSAA model is that design changes are applied when failures are found, and thus the failure data is also indicative of an updated design configuration. This is not exactly true in practice, but there are retrofit campaigns that are completed on the entire fleet in order to improve dispatch reliability. These retrofits are changes to the design of the faulty component, as well as updates made in the practices of manufacturers, airline operators, airports, and regulators.

Mathematically, the Crow-AMSAA model is a Non-Homogeneous Poisson Process (NHPP), which gives the probability of occurrence of n failures within time T,[22]

$$P(N(T) = n) = \frac{\left(\left(-\lambda T^{\beta}\right)^{\wedge} n\right) e^{-\lambda T^{\beta}}}{n!}$$

where, $N(T)$ is the random variable 'number of failures occurred up to time T', and λ and β are parameters to be estimated, based on the available failure event data. The Maximum Likelihood Estimation (MLE) technique is a classical way to proceed for the estimation of the parameters[22] and has been used also here. By grouping the data, the number of failures in each quarter has been used to conduct the analysis. The results of the analysis are shown in Table 2.

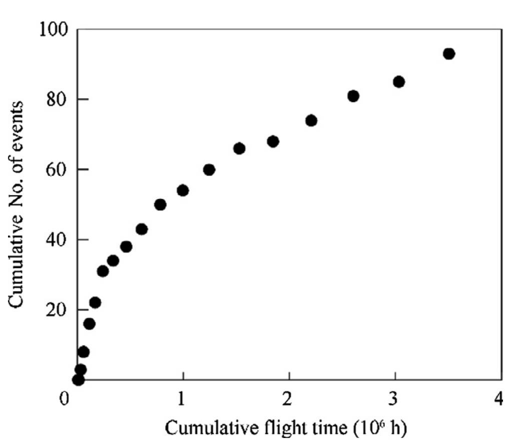

Fig. 1 Number of flight time hours vs. failure events of the 787 aircraft.

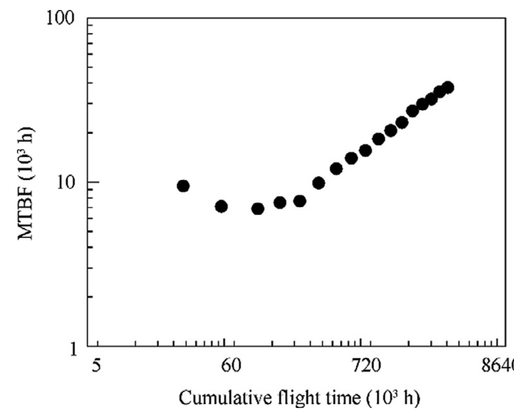

Fig. 2 Duane plot of flight time vs. cumulative mean time between failures (MTBF).

The value of β of 0.7 (<1) in Table 2 suggests a decrease in failure rate over time and is indicative of reliability growth. Examining Fig. 2, it can be seen that the reliability of the 787 aircraft (as measured by the MTBF) was deteriorating until the grounding and started improving after the aircraft returned to service (fourth data point). Other parameter estimates such as DMTBF (demonstrated or instantaneous mean time between failures) and DFI (Demonstrated or instantaneous Failure Intensity) are also reported. Their positive values follow from the corrective actions taken by Boeing during the aircraft grounding period, as well as due to a somewhat natural reduction of those problems that typically emerge during the initial stages of the aircraft operation.

Another metric used in aviation to identify component-level reliability is the Mean Time Between Unscheduled Removals (MTBUR), which is related to those maintenance activities carried out on an aircraft but that were not part of the scheduled maintenance:

$$\text{MTBUR} = \frac{\text{No. of flight hours} \times \text{units installed per aircraft}}{\text{No. of unscheduled removals during that period}}$$

However, we were not able to find any data on the maintenance activities or the components that were removed/replaced. In principle, this data should be made available to the public by the airlines and the FAA.

4. Critical shortcomings in battery certification

Li-ion Batteries (LIBs) were used to power the auxiliary power units and other selected electrical/electronic equipment during ground and flight operations to a larger extent in the 787 than in Boeing's predecessors. Boeing was required to perform safety assessment for its LIBs as per the FAA's Special Conditions 25-359-SC, "Boeing Model 787-8 Airplane; Lithium-Ion Battery Installation". Although Boeing did pass all the requirements set by the FAA, there were shortcomings in the criteria set for failure and guidance on assumptions that manufacturers could use in their testing. These assumptions were not necessarily supported by engineering rationale and led Boeing to pass the qualification tests. For example, there was an assumption that the internal short circuiting in a cell would only cause that cell to vent and not lead to thermal runaway.[11] The battery incident in Japan Airlines showed that Boeing did

Table 2 RGA of 787 post-service re-entry period.

Parameter							Statistical tests	
Model	Analysis	β	λ(h)	Growth rate	DMTBF (h)	DFI	Significance level	Chi-Sq
Crow-AMSAA (NHPP)	MLE	0.70	0.002	0.3	70204	1×10^{-5}	0.1	Passed

not put in place mitigation strategies to avoid or contain the consequences of this assumption, were it to prove wrong in practice.

A confounding factor was the FAA did not consider thermal runaway to be a potential consequence of cell short circuit. Hence, FAA certification engineers did not require thermal runaway testing as part of compliance demonstration. This contributed to a lack of clarity in guidance to certification engineers on translating specific worst-case scenarios to compliance deliverables, such as which test procedure to follow and which test reports to provide in the certification plan. In addition, there were manufacturing defects and absence of thermal management systems. There were also inconsistencies found in the Electric Power System (EPS) safety assessment provided by Boeing with respect to the compliance with the FAA Advisory Circular (AC) 25.1309, "System Design and Analysis".[11]

Eventually, Boeing redesigned the battery system and had it approved by the FAA. The FAA issued a new airworthiness directive to install the redesigned batteries on all 787 airplanes to be returned to service.

5. Reliability assessment

From the various documents and trends, it can be argued Boeing did not adopt an effective Reliability Program Plan (RPP), where best practice tasks are implemented to produce reliable products.[23] Boeing opted to widen its supplier base and reduce costs by including manufacturers who were new to the aircraft development industry. The events that led to delays during manufacturing and failures during operation are a testament to Boeing's flawed practices.

The following sub-sections describe Boeing's practices in planning and managing the development cycle and supply chain, the challenges with information sharing with a tiered, globally dispersed supplier base, with developing a proper diagnostics and prognostics approach, with testing of new technologies, and with oversight of a complex product development process.

These factors are identified as potential causes of the operational problems. Furthermore, these deficiencies are seldom independent of each other and can have a compounding effect on product reliability.

5.1. Short development cycle and highly complex supply chains

Boeing intended to reduce to four years the development period of the 787 (its predecessor 777 was developed in six years) and, at the same time, reduce the development costs from $10 billion to $6 billion.[24] To do so, Boeing decided to adopt a new supply chain and product development structure. This resulted in a new supply chain structure of approximately 50 tier-1 strategic partners, and many more tier 2, 3, and 4 suppliers, which they would have little or no say over. On top of this, 30% of the supply chain was outsourced to manufacturers outside the USA.[24]

The supply chain structure was responsible for the 2.3 million parts required to build and assemble the aircraft.[25] The tier-1 partners, such as Alenia Aeronautica (Italy), Messier-Dowty (France), Rolls-Royce (Britain), and Mitsubishi Heavy Industries (Japan), served as integrators responsible for assembling entire subsystems, each having its own specific supply chain.[26]

The time and cost of production was intended to be reduced by delegating the design, development, and component manufacturer selection process to sub-system suppliers.[7] The tier-1 partners would be responsible for delivery of complete sections of the aircraft to Boeing, who would then perform the final assembly.[7]

The rationale behind this business strategy was that the best process skills were increasingly being found outside Boeing factories in the USA, according to Mike Bair, then vice-president of the 787 program.[6] This created new supplier bases which were either new to Boeing or new to the aircraft industry as a whole. This included the Lithium-Ion Battery (LIB) manufacturer GS Yuasa, which was selected by Thales Avionics to supply batteries for powering auxiliary devices. As will be discussed later, the inexperience of GS Yuasa in dealing with aircraft products led to inappropriate specification of batteries based on the reliability data from other industrial applications.

This new supply chain structure was a departure from traditional practice, in which the manufacturer was responsible for the assembly of the major subsystems. This tiered system is a complex structure of interacting technical and organizational artifacts. The new and more complex supply chain led to intricacies in assembling many components from different suppliers into a large subsystem that was manufactured by a different supplier. For example, Boeing contrived a modular design for the 787 to enable engine interchangeability between Rolls-Royce and GE engines on the same aircraft. As a result, the interchanging process actually took 15 days against the intended 24 h, because of technical incongruities due to multiple supply chain participants.[9] Similarly, several "shimming" issues were found when trying to assemble parts from different suppliers, due to the lack of conformity to tolerances and understanding of design requirements [9].

5.2. Lack of accurate and timely information sharing

Since the supply chain was spread across the globe, there were challenges in synchronizing changes to the design requirements down through the supply chain and production information back up through the supply tiers.[9] Boeing tried addressing this challenge by implementing a web-based tool called "Exostar", which allowed the suppliers to enter their relevant information such as design and production requirements and production status of the components. Contrary to the intended effect, this data sharing process did not improve the visibility across the supply chain due to the discrepancies in accuracy and delay and misinterpretation of data from the tool. The lack of familiarity of aerospace manufacturing standards and cultural differences in terms of workmanship among suppliers from various locations contributed to this inefficiency in data sharing.[7,9]

For example, the FAA found discrepancies in the dissemination of requirements for the primary electrical power panel from Boeing to United Technologies Aerospace Systems (UTAS), then from UTAS to sub-tier supplier Equipment et Construction Electrique (ECE) and from ECE to its printed circuit board component supplier. The FAA review team found deficiencies also in the process of passing requirements down the levels of suppliers leading to 1) weak design, which then manifested as part malfunctions once they entered service, 2) variability in manufacturing, and 3) anomalous behavior of parts.

The bottom-up information flow was similarly hindered as seen in the instance where Vought, a tier-1 supplier, entered into a contract with Advanced Integration Technology (AIT) as a tier-2 supplier to aid in integrating systems. AIT was assigned the responsibility of communicating with other tier-2 and tier-3 suppliers on behalf of Vought.[7] But due to cultural and geographical differences, the suppliers did not always communicate the proper information. These differences led to delays in supplying parts, which were not visible to Boeing and kept Boeing from responding to delays in a timely manner, and in understanding requirements changes.

5.3. Lack of relevant data

Data collection for system Health and Usage Monitoring Systems (HUMS), and Prognostics and systems Health Management (PHM), provides the opportunity to assess the state of operation of the airplane and its components, and predict the reliability and safety.[23] However, this was not well executed in the Boeing 787 aircraft. For example, the FAA, Boeing, and Japan's Transport Ministry conducted a thorough analysis on the root cause of failure of the lithium-ion batteries in the 787.[12] However, they were unable to identify the root cause of the thermal runaway event. Many issues such as production quality problems of contamination, electrolyte evaporation, and over-voltage loads were hypothesized, but were not proven to be conclusive.[27] The Flight Data Recorder (FDR) collected 363 different measurements before and after the battery fire incident of which only two, the DC feed load current and the APU battery DC bus voltage, were directly related to the faulty batteries.[27] The FDRs were not designed to collect individual cell data from the Battery Management System (BMS), which could have given insight into the specific battery that caused the thermal runaway.

5.4. Lack of valid testing on innovative technologies

The FAA review team observed that both existing and new technologies incorporated in the 787 aircraft were not tested for the specific 787 application. The success of these technologies, either in other applications or in previous Boeing aircraft, was assumed to be carried over to the 787 as well.[9] LIBs, which have become one of the major concerns for 787 reliability, were adopted from another industrial application, and there were no failures reported in such application. Based on the data from this industrial application, GS Yuasa assumed a Poisson distribution for the LIB failure time and estimated a failure rate of less than 1 failure in 10 million flight hours.[28] However, by the time the 787 was grounded in 2013, the failure rate of the LIBs was 3 in 250,000 hours. The estimate of less than 1 in 10 million hours was based on a 60% confidence interval, while a 90% confidence interval or higher is usually suggested for critical reliability applications such as those of avionics.[28]

The level of DO-160 testing required was established at the time Boeing submitted the application to design, test, and build the 787 to the FAA, which would have been around 2003 or 2004. Guidance on how to test LIBs was issued in AC 20-184 in October 2015. This could have led to a situation where technology outpaced the regulations.

While the new technologies were given slack in testing, the before quality of the processes that was considered ‘‘stable’’ was inspected the same technician who carried out the process.[29] One of the former Department of Transportation inspectors stated that in many cases these self-inspections were actually not conducted and were passed on by the workers who executed the process. This kind of flawed practices has led to many mistakes in the production line as per the Boeing workers.[29]

Finally, the reliability assumptions for the electronics and the testing of the electronics, including the battery, are of grave concern, in part because Boeing has traditionally assumed the constant failure rate and used the outdated military handbook 217 for its reliability and safety calculations. This handbook was last updated in 1997 and was considered inaccurate and unacceptable for use by the military by a National Academy of Sciences study[30,31] and for aviation industry as well.[31] The handbook based method uses field failure data of un-related applications to determine a point reliability value of aircraft without considering its specific complex use conditions.

5.5. Difficulty in fault detection

The 787 aircraft is a complex system with about 2.3 million parts supplied and assembled from manufacturers around the globe.[24] The CSRT noted[9] that when an issue was reported during the service of the aircraft, the suppliers removed the parts they deemed to be defective, but often found there was no fault. This could be due to the intermittent nature of electronics systems,[32–34] In fact, it has been noted that cases of no-fault-found on airplanes can be as high as 80% and Boeing often replaces electronics Line-Replaceable Units (LRUs) with LRUs that were flagged as failed but were no-fault-found once they were removed. This practice is problematic considering the wear out and intermittent failure nature of electronics.

5.6. Lack of balance between autonomy and oversight

In Boeing's 787 development model, the integration of subassemblies and final assembly was critical for the hardware and software from different suppliers to fit together and operate properly. This required a balance of providing autonomy to the suppliers to meet the design requirements and keeping a close oversight on the supplier processes. However, Boeing did not opt for on-site supplier, supports which led to absence of a bi-directional technical communication to keep the quality of the parts and sub-assemblies in check. [35] For example, Mitsubishi Heavy Industries stated that Boeing did not adopt Mitsubishi's early testing and diagnosis principle,[35] which in turn led to design flaws being carried over to next tiers of assemblies and eventually to aircraft operation in the field.

6. Conclusions

Evaluating the reliability of a complex system made of multiple components, like an aircraft, is very difficult especially during the development stages. As a matter of fact, many factors contribute to the difficulty of evaluating reliability during product development: tight scheduling for contracted deliveries, requirements on testing and validation, pressures for cost reduction, multiple tiers of suppliers of the many parts constituting the system, challenges with accurate and timely data sharing, innovative technologies requiring specific testing procedures, and others.

In this paper, operational problems with the Boeing 787 aircraft have been analyzed to identify different manufacturing and organizational factors that have impacted the reliability performance of such a complex system in operation. Reliability metrics, such as cumulative Mean Time Between Failures (MTBF) and cumulative number of failure events, have been estimated from publicly available data. A reliability growth analysis has been performed to study also the impact of corrective actions carried out by Boeing on the performance of the 787 aircraft.

Undoubtedly, there were enormous challenges inherent in the development of a new product like the 787. And with the increase in reliability as one of the goals of the 787 project development, Boeing invested significantly in changes to its engineering and business structure. However, the problems that then occurred in the aircraft's operation have emphasized the need for strengthening the focus on quality and for developing a reliability-centric approach to supplier selection, training, and production management.

In this regard, some practical guidelines follow. Suppliers should consider IEEE 1332-2012, JA1000-201205, and IEEE 1624 in the development stages. The IEEE 1332-2012 document provides a standard set of reliability program objectives for use between customers and producers, or within product development teams, to express reliability program requirements early in the development of electronic products. SAE adopted the IEEE standard and released it as JA1000, which is followed by various industry sectors. OEMs should take necessary steps to validate the ability of the suppliers to meet the reliability requirements. IEEE 1624-2008 Standard for Organizational Reliability Capability provides guidelines for assessing, in a systematic manner, the effectiveness of an organization's reliability practices in ensuring or exceeding product reliability requirements. Avoiding misinterpretations and having detailed information on inputs and assumptions for predicting the reliability of hardware is essential in understanding the risks associated with using the prediction results for future product integration and ensuring overall system reliability.

Manufacturers can ensure consistent prediction and reporting of reliability of hardware across product development teams by following established standard procedures such as IEEE 1413-2010. IEEE 1413 aids in providing sufficient information on inputs, assumptions, and uncertainties in the estimated reliability. Further, aerospace standards such as AS9100, based on ISO 9001:2015, are dedicated to ensuring product quality and process management for aircraft parts manufacturers.

Finally, while the grounding of the 787 in 2013 focused the spotlight on Li-ion batteries, and on the complexity of the supply chain, there were also concerns pertaining to how the airplane could be certified within three months without knowing the root causes of failure. This is more so relevant today, in light of the recent concerns with the 737 MAX, and the role of Boeing and the FAA in understanding and evaluating reliability and safety issues.

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Appendix A

Table A1 Events associated with the Boeing 787 Dreamliner, November 2011–January 2013.

Date	System	Component	Failure mode	Event description	Refs.	Airline
November 2011	Landing gear	Hydraulic valve	Failure to open/close	The ANA-operated flight had to make a second attempt at landing using alternate extension backup, after a faulty hydraulic valve could not deploy the landing wheel.	36	All Nippon Airways Registration (ANA): JA801A
February 2012	Fuselage	Stiffening rods	De-lamination	Stiffening rods/shear ties used to connect the fuselage skeleton with the skins had delaminated from the skins.	37	All Dreamliner Aircraft
July 2012	Engine ancillary system	Gearbox	Corrosion	ANA grounded five of its 11 Dreamliners, due to corrosion of parts of the gearbox used to drive ancillary systems in the Rolls Royce Trent 1000 engine.	38	ANA

Table A1 (*continued*)

Date	System	Component	Failure mode	Event description	Refs.	Airline
July 2012	GEnx engine	Fan shaft	Fracture	One of the shafts that connect the fan and the booster to the low-pressure turbine of the dual-shaft GEnx engine fractured at the rear end of the threads where the retaining nut is assembled. This occurred during a pre-delivery taxi test.	39	Pre-delivery
September 2012	Engine ancillary system	Hydraulic system	Leak	ANA aborted a flight from Okayama Airport after detecting smoke-like emission due to misting of oil dripping from hydraulic pump on the hot engine	40	ANA: JA801A
December 2012	Control system	Electrical panel	Alarm	Aircraft headed from Houston to Newark, emergency-landed in New Orleans after a false alarm indicated generator failure. Short circuiting on an electrical panel was found to be the cause of the false alarm. The same problems were reported in one of the Qatar Airways aircraft and another United Airlines aircraft in the same month.	41	United Airlines - Registration N26902; Qatar – Registration A7-BCA
December 2012	Engine ancillary system	Fuel system	Leak	FAA ordered an inspection into improperly installed fuel line connectors after finding that it could result in leaks leading to fuel exhaustion, thermal runaway, engine power loss or shutdown	42	All Boeing Dreamliners
January 2013	Li-ion battery system	Battery	Smoke	Heavy smoke was found emitting from the electronic equipment bay in the aft cabin of a parked aircraft at Logan International Airport, Boston. The smoke was attributed to the thermal runaway caused by internal short circuiting of one of the APU Li-ion battery cells	39	Japan Airlines Registration: JA829J
January 2013	Li-ion battery system	Battery	Smoke	The flight on its way to Tokyo from Yamaguchi Ube Airport received an Engine Indicating and Crew Alerting System (EICAS) message reporting battery failure accompanied by an unusual smell in the cockpit. Battery heating and thermal runaway were reported to be the probable causes for smoke.	39	ANA: JA804A

Table A2 Events associated with the Boeing 787 Dreamliner, April 2013–August 2015.

Date	System	Component	Failure mode	Event description	Refs.	Airline
September 18 2013	Engine ancillary system	Fuel system	Alarm	The flight powered by two Rolls-Royce Trent 1000-67B turbofan engines experienced a maintenance status message "ENG FUEL FILTER R" on its way from Beijing to Warsaw Chopin Airport. Later on, a maintenance investigation found that the engine fuel filter in the right engine had not been installed. Further examination revealed that the fuel filter was not installed in the left engine as well.	13	LOT Polish Airlines Registration: SP-LRB

(*continued on next page*)

Table A2 (*continued*)

Date	System	Component	Failure mode	Event description	Refs.	Airline
September 19 2013	Engine ancillary system	Fuel system	Alarm	Following the SP-LRB incident, this flight was checked the next day to reveal that there were no fuel filters installed in this aircraft too.	13	LOT Polish Airlines Registration: SP-LRC
October 10 2013	Electrical	Unknown	Toilets fail to flush	Aircraft headed from Moscow to Tokyo had to land midway due to electrical problems. It was reported that toilets did not flush due to an electrical failure.	43	JAL: JA832J
January 20 2014	Communications	Transponder	Failure to function	The aircraft headed from London to Delhi vanished completely from the secondary ATC radar due to transponder failure. After negotiating with the air traffic authorities, the crew was asked to return to London and fix the issue before flying	44	Air India Registration: VT-ANE
February 5th 2014	Control System	Flight management	Failure to function	The aircraft headed from Australia to India landed midway in Malaysia due to the failure of all three flight management control systems.	45	Air India Registration: VT-ANJ
October 17 2014	Communications	Unknown	Failure to function	The aircraft headed from Delhi to Rome had to be intercepted by the Italian Air Force due to a lack of communication. It was later reported that the aircraft had lost its communication capability due to a technical malfunction.	46	Air India Registration: VT-ANQ
January 22 2015	GEnx Engine	Unknown	Unknown	The flight, which was bound to Mumbai from London, had to divert to Budapest, Hungary, due to failure of the right engine, General Electric GEnx-1B.	47	Air India Registration: VT-ANL
February 23rd 2015	Air supply	Unknown	Drop in cabin pressure	The aircraft was stopped after takeoff at FL240, citing a drop in cabin pressure.	48	Aeromexico: N961AM
March 19th 2015	Communications	Transponder	Failure to function	The aircraft that was scheduled from Madrid to Mexico City made an emergency landing in the Azores when the crew complained of an electrical failure. The radar data had suggested that the aircraft was no longer able to provide position and Mode-S data with its transponder.	49	Aeromexico Registration: N964AM
April 30, 2015	Control System	Software	Failure to function	In Boeing's own laboratory testing, conducted after the planes were sold to the customer, it was found that if the generator was operated for around 8 months continuously, the control unit software could overflow and go into a fail-safe mode. This means that the generator could stop working and power to the aircraft could be cut off, even if the plane were in flight.	50	All 787 s
June 25, 2015	Electrical	Flight controls	[Unknown]	The aircraft flying from Melbourne to New Delhi had to land 70 minutes after takeoff due to a technical issue. It was reported that there was a minor issue in flight controls that did not allow the airline to continue the flight.	51	Air India Registration: VT-ANR
July 17th 2015	Landing system	Main Gear	Failure to function	The aircraft landed 45 minutes after takeoff due to malfunction of the left-hand main gear. It was reported that the drag brace actuator had become defective and had to be replaced.	52	Air India Registration: VT-ANV
January 29th 2016	Engine ancillary system	Anti-ice	Imbalance on turbine	A few of the blades in one of the GEnx-1B engines used in a JAL aircraft from Vancouver to Tokyo experienced ice formation. This led to partial ice shedding and, in turn, imbalance in the turbine which caused rubbing of the blades onto the fan case surface	53	Japan Airlines Registration: JL17

Table A3 Failure times calculation (Based on problem reports from Ref. 54.

Year	Fiscal year quarter (qtr.)	Period	Deliveries	End of year reported deliveries	Cumulative deliveries	End of year reported cumulative deliveries	Est. no. new in service	Hrs. flown in qtr.	Cum. hrs. flown	Events in qtr.	Cum. events	MTBF
2011	3	Jul-Sept 2011	1		1							
	4	Oct-Dec 2011	2	3	3	3	1	1095	1095			
2012	1	Jan-Mar 2012	5		8		3	3285	4380	0	0	0
	2	Apr-Jun 2012	6		14		8	8760	13,140	0	0	0
	3	Jul-Sept 2012	12		26		14	15,330	28,470	3	3	9490
	4	Oct-Dec 2012	23	46	49	49	26	28,470	56,940	5	8	7118
2013	1	Jan-Mar 2013	1		50		49	53,655	110,595	8	16	6912
	2	Apr-Jun 2013	16		66		50	54,750	165,345	6	22	7516
	3	Jul-Sept 2013	23		89		66	72,270	237,615	9	31	7665
	4	Oct-Dec 2013	25	65	114	114	89	97,455	335,070	3	34	9855
2014	1	Jan-Mar 2014	18		132		114	124,830	459,900	4	38	12,103
	2	Apr-Jun 2014	30		162		132	144,540	604,440	5	43	14,057
	3	Jul-Sept 2014	31		193		162	177,390	781,830	7	50	15,637
	4	Oct-Dec 2014	35	114	228	228	193	211,335	993,165	4	54	18,392
2015	1	Jan-Mar 2015	30		258		228	249,660	1,242,825	6	60	20,714
	2	Apr-Jun 2015	34		292		258	282,510	1,525,335	6	66	23,111
	3	Jul-Sept 2015	37		329		292	319,740	1,845,075	2	68	27,133
	4	Oct-Dec 2015	34	135	363	363	329	360,255	2,205,330	6	74	29,802
2016	1	Jan-Mar 2016	30		393		363	397,485	2,602,815	7	81	32,134
	2	Apr-Jun 2016	38		431		393	430,335	3,033,150	4	85	35,684
	3	Jul-Sept 2016	36		467		431	471,945	3,505,095	8	93	37,689
	4	Oct-Dec 2016	0	104	467		467	511,365	4,016,460		93	43,188

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